Generating atmospheric neutrinos with dunetpc

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Short introduction

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- currently working on a sensitivity study for one model of Boosted Dark Matter from the sun
- neutral current interactions from atmospheric neutrinos are a main background
- ... so we go, take dunetpc, generate events and...

Software

Used software:

- dunetpc `v07_06_01`
- job configuration: `prodgenie_atmnu_max_dune10kt.fcl`:
  - DUNE far detector, full size (10 kton, not $1 \times 2 \times 6$)
  - Bartol maximum atmospheric neutrino flux:
    20 cos θ bins, 40 energy bins, ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$
  - limits the generation to into the cryostat volume
- pulls in:

genie	`v2_12_10c`	
genie_phyopt	`v2_12_10`	
genie_xsec	`v2_12_10`	`-q DefaultPlusValenciaMEC`
dk2nugenie	`v01_06_01f`	`-q dkcharmtau`

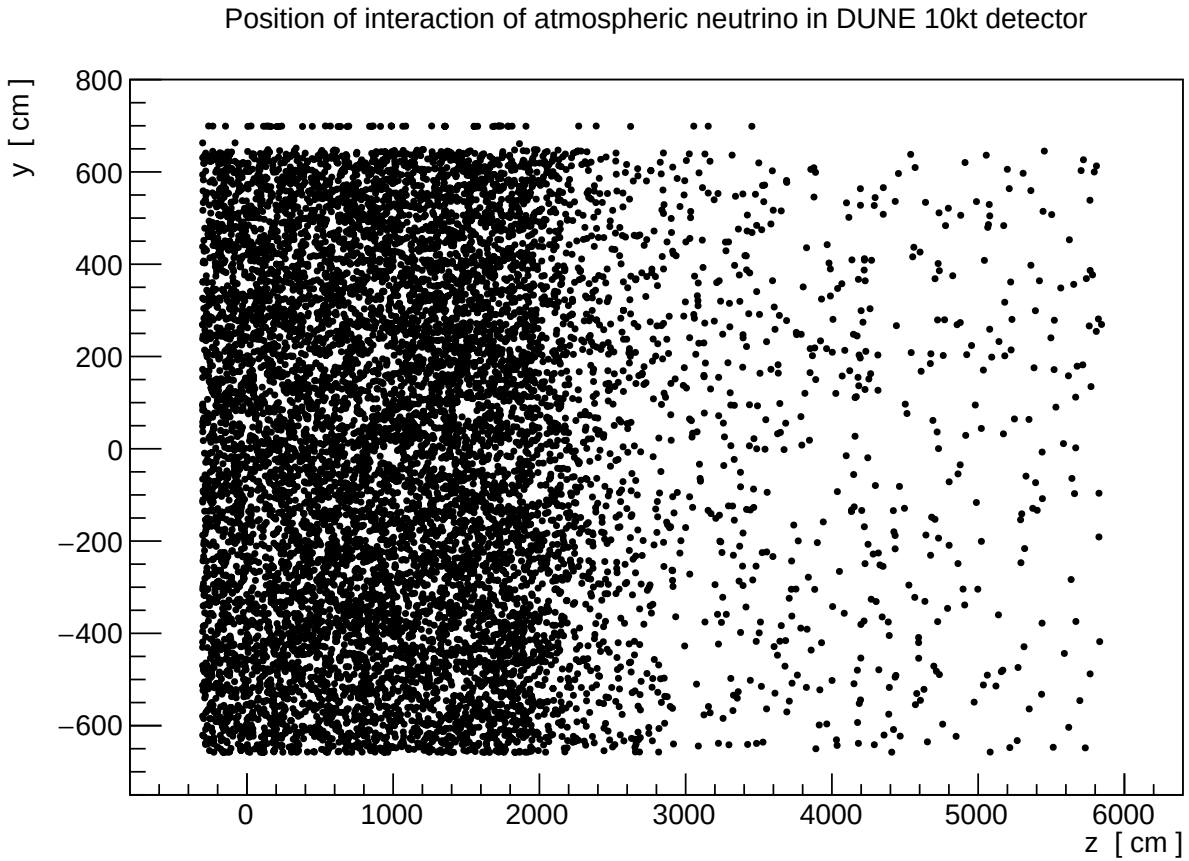
Structure of `prodgenie_atmnu_max_dune10kt.fcl`

The configuration files for atmospheric neutrinos are twofold:

- `prodgenie_atmnu_max_dune10kt.fcl` for 10 kton detector:
  - sets the services for DUNE 10 kton detector
  - inherits from a standard GENIE generation configuration
  - tells GENIE we are generating atmospheric neutrinos
  - sets generation list to `Default+CCMEC`
  - sets the flux to Bartol
  - fixes the generation to the cryostat volume
- `prodgenie_atmnu_max_dune10kt_1x2x6.fcl` for reduced detector:
  - changes the geometry description (`Geometry` service)

First generation: out of the box

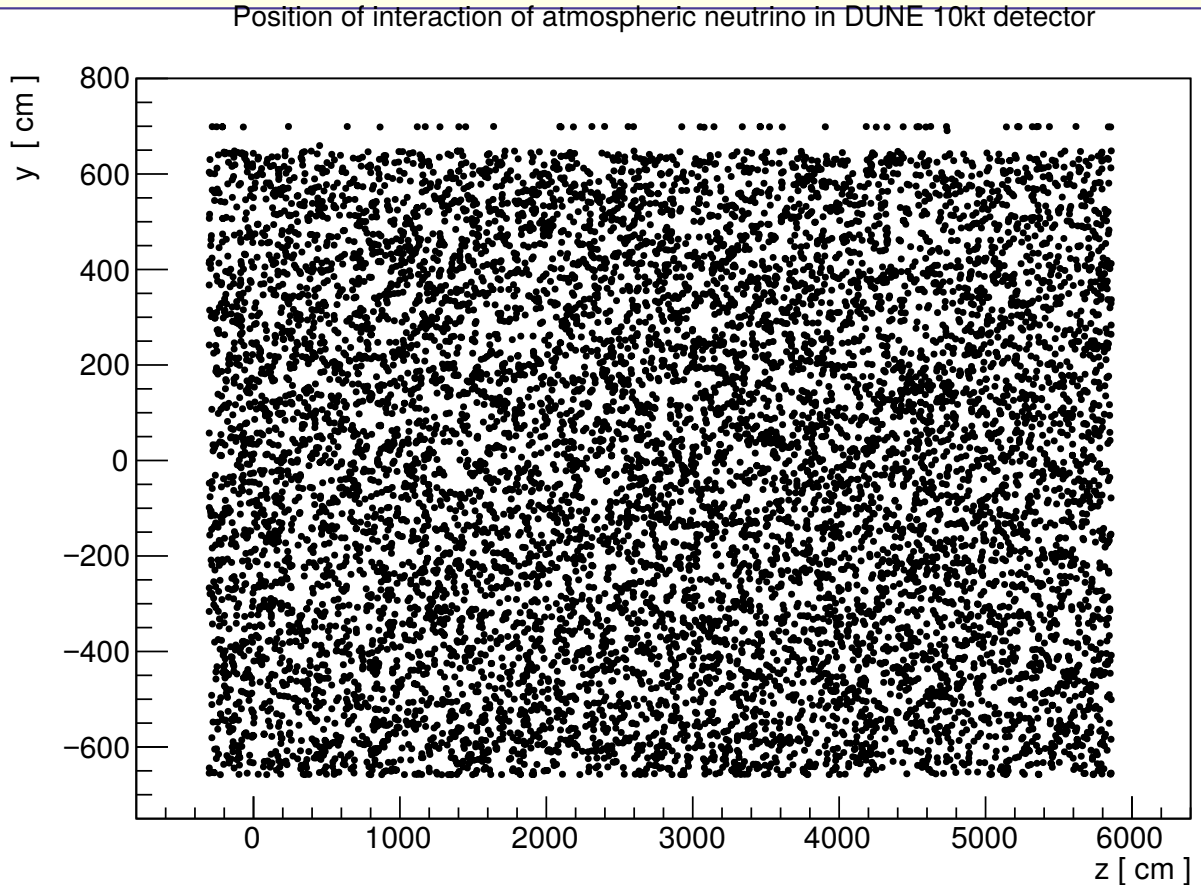
Generated 10000 events, 0.4"/event...



It turns out, the configuration is tuned to the $1 \times 2 \times 6$ geometry!

Second generation: fixed flux window

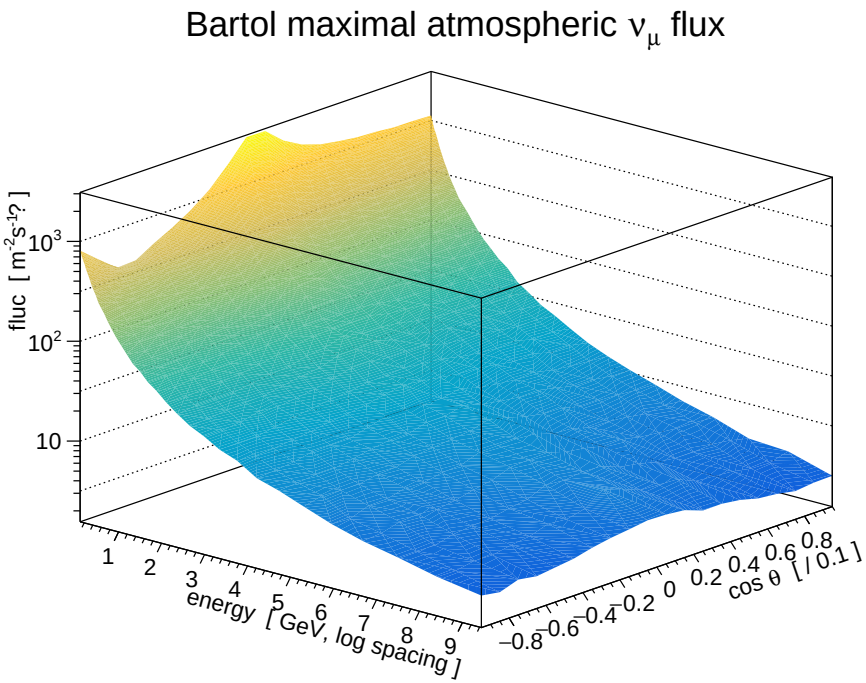
```
physics.producers.generator.Rl: 70 # meters
physics.producers.generator.Rt: 70 # meters
```



fixes the problem, but it's very inefficient[1] (now 2–3"/event).

[1] Due to the fact that the origin of coordinates is on a border of the detector, and the way GENIE casts the atmospheric neutrino flux.

Digression: Bartol flux parametrisation



Maximal ν_μ flux as represented in the flux file (it should be an histogram, but printing it this way was a ROOT one-liner...)

Bartol flux is parametrised on:

energy (in logarithmic bins) between 0 and 10 GeV

angle *from the vertical* ($\Delta\cos\theta = 0.1$)

azimut no parametrisation: flux presents cylindrical symmetry

Note the (asymmetric) structure in $\cos\theta$.

Second digression: DUNE coordinate system

The active volume of the far detector is:

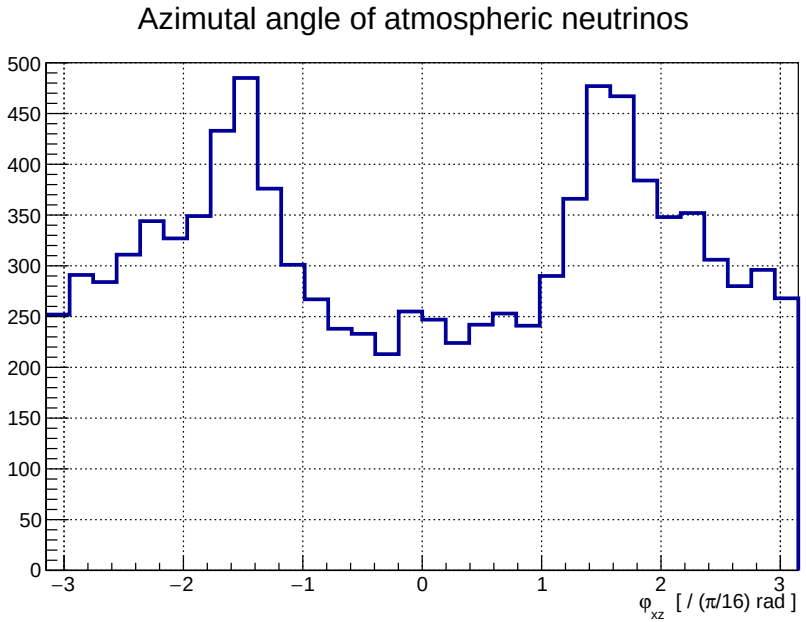
- about 12 m on $\hat{x}$ (drift direction)
- about 12 m on $\hat{y}$ (vertical)
- about 60 m on $\hat{z}$ (beam direction)
- active volume (200 TPCs) is 10000 m^3 (14 kton of argon)
  $\rightarrow$ the standard label 10 kton is the *fiducial* volume

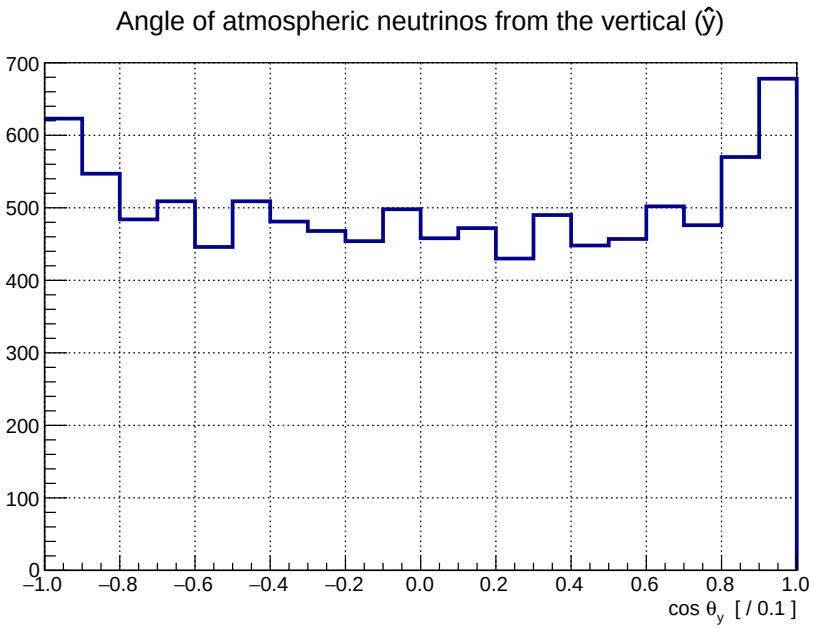
Focus here is on the labelling of the axes, because...

GENIE atmospheric flux driver assumes $\hat{z}$ to be vertical, and the parameter in the flux description to be $\cos\theta_z$

Second generation: orientation

Is this inconsistency a problem? We work in DUNE coordinates:





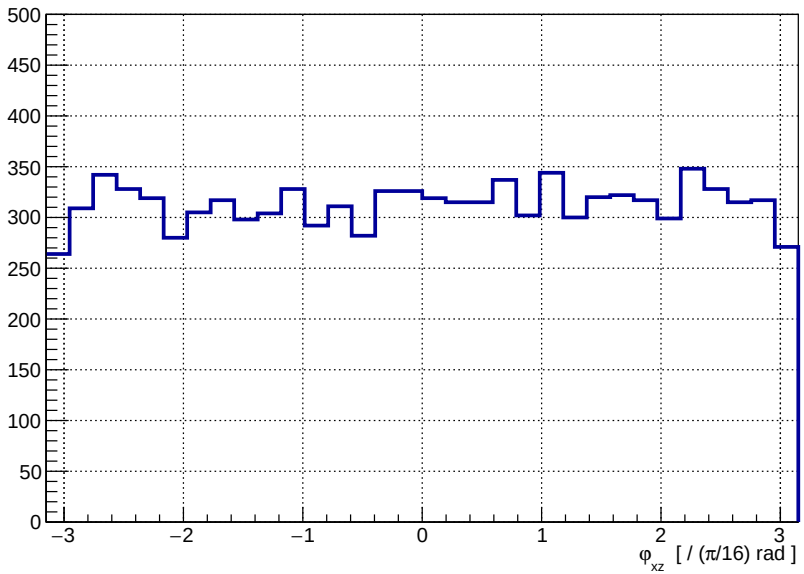
Expect distribution uniform in φ_{xz}... ... and structure in cos θ_y

So, `GENIEHelper` does not fix it in the background.
GENIE believes DUNE 60 m tall, DUNE believes sky is toward Chicago.

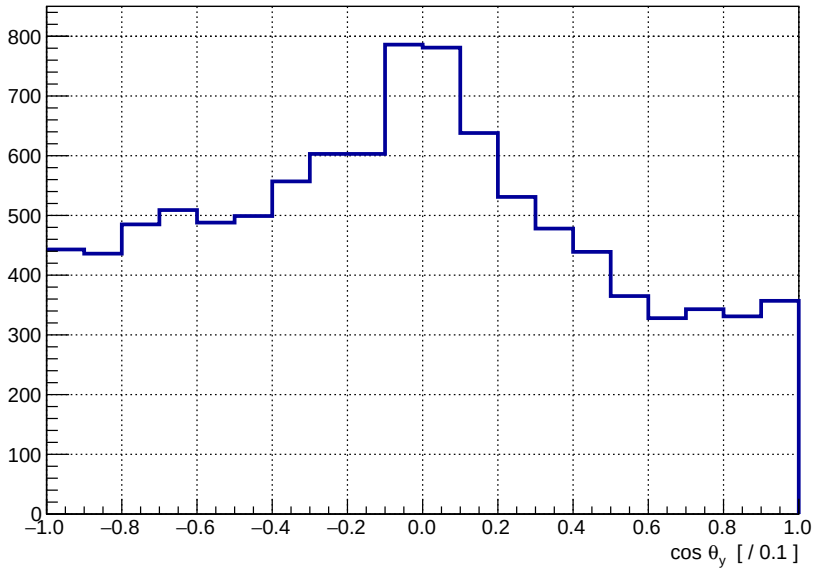
Third generation

```
physics.producers.generator.FluxRotCfg: "newxyz"
physics.producers.generator.FluxRotValues: [
  +1.0, +0.0, +0.0,   # new x axis in old coordinates: be nice and fix thir
  +0.0, +0.0, +1.0,   # new y axis in old coordinates: vertical
  +0.0, -1.0, +0.0    # new z axis in old coordinates: westward
  ]
```

Azimutal angle of atmospheric neutrinos



Angle of atmospheric neutrinos from the vertical ($\hat{y}$)



Expect distribution uniform in φ_{xz}... ... and structure in $\cos\theta_y$

This rotation points DUNE toward east, about 9 ° off Fermilab (“ToDo”).

Flavour composition

Our 10000 event sample appears to be made of:

	CC	NC
ν_μ	1038	398
$\bar{\nu}_\mu$	280	169
ν_e	597	206
$\bar{\nu}_e$	126	72

Aaron's numbers (total: 2886 events)

	CC	NC
ν_μ	3581	1321
$\bar{\nu}_\mu$	1048	594
ν_e	2119	671
$\bar{\nu}_e$	434	232

Our sample (total: 10000 events)

	CC	NC
ν_μ	1033	381
$\bar{\nu}_\mu$	302	171
ν_e	612	194
$\bar{\nu}_e$	125	67

Our sample (scaled to 2886 events)

This leaves us comfortable, since it matches Aaron Higuera's numbers[2] presented at DUNE colaboration week on September 25, 2018.

[2] https://indico.fnal.gov/event/16526/session/36/contribution/157/material/slides/0.pdf

Flux normalisation

`GENIEGen` reports an exposure time, which according to the code documentation is in seconds:

```
%MSG-i GENIEHelper:  PostEndJob 15-Oct-2018 04:33:50 CDT ModuleEndJob
 Total Exposure 3.98375e+08 GMCJDriver GlobProbScale 1.01482e-08 FluxDrive
%MSG
```

Is this reliable?

- Aaron estimates the flux (before oscillation) to be $\approx$ 2800 interactions/year in 10 kton of argon
- the log file suggests $8 \cdot 10^4$ s (for 10000 events $\rightarrow$ 971 interactions/year in all cryostat — steel, 17 kton of argon, ...)
  $\rightarrow$ no statistical uncertainty provided, but after 10000 events it should be “small”

This leaves us uncomfortable, since it does *not* match Aaron’s numbers.
We are investigating what the differences might be.

Summary

- the standard DUNE 10kt atmospheric neutrino generation configuration does not cover the full detector
- all standard DUNE atmospheric neutrino generation configurations have wrong flux orientation
- I will commit a branch `feature/gp_AtmoFluxFixes` in dunetpc with the changes mentioned in this talk
- we still have to understand the meaning of the normalisation suggested by GENIE

Many thanks to Aaron Higuera and Hirohisa Tanaka for the discussions and help!